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Cure-State Monitoring and Water-to-Cement Ratio Determination of Fresh Portland Cement-Based Materials Using Near-Field Microwave Techniques

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***Abstract*— Quick and nondestructive determination of cure-state and water-to-cement (w/c) ratio in fresh Portland cement-based materials is an important issue in the construction industry since the compressive strength of these materials is significantly influenced by w/c ratio. This is especially true since current techniques are not reliable and require *a priori* testing of test specimens as calibration for subsequent on-site monitoring of a cast in-place structure. Recently, the sensing of Portland cement-based materials using microwave techniques has received much attention. Microwave nondestructive techniques have already shown the potential for determining w/c ratio, sand-to-cement (s/c) ratio and coarse aggregate-to-cement (ca/c) ratio in cured cement paste, mortar, and concrete. In this paper, the results of a study demonstrating the potential for early determination of cure-state and w/c ratio of Portland cement-based materials, using a near-field microwave inspection technique, are presented. This technique utilizes the reflection properties of an open-ended rectangular waveguide probe radiating into Portland cement-based materials at 5 GHz (G-band) and 10 GHz (X-band). The results demonstrate the ability of near-field microwave sensing techniques to determine the state of hydration of cement paste and concrete with 0.50 and 0.60 w/c ratios and varying aggregate contents. In fact, it is shown that cement-based materials that have been moist-cured for three days and then left to cure at ambient temperature and humidity for the remainder of the prescribed 28-day curing period, are fully cured after only 12 days. An empirical formula relating the magnitude of reflection coefficient to the curing time is presented. Using this empirical relationship, the w/c ratio of cement paste and concrete can be unambiguously determined when daily monitoring of the reflection properties of the specimens is performed. The potential for utilizing this technique for on-site monitoring of cure-state and w/c ratio (and compressive strength) determination is also discussed.**

***Index Terms*—Concrete, cure state, microwave inspection, nondestructive, water-to-cement ratio.**

I. INTRODUCTION

CONCRETE is one of the major materials used in construction globally. It is comprised of cement, water, fine aggregate and coarse aggregate. The aggregates act as inert filler materials while the cement and water combine into a cement paste binder. One of the most important parameters influencing the behavior of concrete, from its compressive strength point of view, is its water-to-cement w/c ratio (measured by weight) used in a concrete mix.

The compressive strength of concrete is almost always the vital parameter in the structural design of concrete structures, and is specified for building code compliance. When the compressive strength is specified, it is given as the strength after the concrete has cured for 28 days. In many practical applications it is of interest to know the strength of concrete before the prescribed 28 days. Examples of this are the removal of concrete form work around columns, application of prestressing forces, and application of loads on a structure.

In practice, the w/c ratio is the largest single factor influencing the strength of fully compacted concrete (concrete with about 1% air voids) [1, p. 270]. All other factors being the same, the strength of concrete decreases as the w/c ratio increases. The w/c ratio also has an effect on the relative gain of strength of concrete over time. A concrete with a lower w/c ratio will gain strength quicker than one with a higher w/c ratio.

One standard method to determine the strength of concrete is to have a concrete cylinder made from the same material as the structure being built. The cylinder is then loaded using a cylinder testing machine until it yields. The results give a measure of the potential strength of the concrete, not the actual strength of the structure, since they are not cured the same [1]. Another method used is to remove and test a core from the structure, which is destructive in nature. These core strengths can be used as an indication of the *in-situ* strength, but are not easily correlated to the 28-day strength [1]–[3]. Another method used is to make a cast-in-place cylinder in the structure in a push-out mold. Even in this case, these cylinders do not have the same compaction as the concrete used in the structure, and therefore will have a different strength. Also, additional work is required to patch up the structure. Accelerated curing techniques can be used as an early indication of the 7- or 28-day strength of concrete. They involve using heat and pressure, but do not yield any information on the cure-state over the 28-day period.

All of the tests described do not necessarily give direct information about the concrete in the actual structure, even though this is the sought-for parameter. Field-cured specimens help, but require tedious preplanning. Cores yield useful information, but are labor intensive and destructive in nature. To circumvent these problems many nondestructive *in-situ*

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tests have been developed, although some involve minor damage to the structure. These tests include: rebound hammer, penetration resistance, pull-out, postinstalled, and ultrasonic pulse-velocity techniques [1], [4]–[6]. The results from these tests for strength measurements are, for the most part, only comparative in nature and need to be correlated with actual tests of cores or specimens. Often several of these techniques need to be used together to obtain meaningful results.

The w/c ratio of a concrete mix is typically given at the batch plant. However, there may exist discrepancies in the intended ratio due to incorrect weighing of the constituents at the batch plant, or deliberate changing of the water content in the field. Therefore, it is sometimes useful to determine the actual w/c ratio of fresh concrete. Several methods are available for testing fresh concrete, but they have serious limitations in the field [1, p. 235]. One chemical method set by the American Society for Testing and Materials, ASTM C 1078-87 [7], gives the value of cement content in fresh concrete. When this information is used with the amount of free water in the fresh concrete, found from ASTM C 1079-87 [8], an estimate of the w/c ratio may be found. These ASTM methods require equipment and operator skills which are not commonly found in the field [1, p. 235]. Several other methods are outlined in [1], but this concludes with the following: "We can see that there exist no reliable and practical procedures for the measurement of the water/cement ratio of fresh concrete."

When the concrete has cured, there is no method that directly measures the amount of cement present. The methods prescribed by ASTM [9] and the British Standards Institution [10] for the determination of Portland cement, generally yield inconclusive results [1, p. 635]. If the w/c ratio for a concrete sample is of interest, the original amount of water needs to be found. The original amount of water is the sum of the combined water in the cement and the volume of the capillary pores (the remainder of the water). This original water content, when combined with the amount of cement present, will give an indication of the w/c ratio. One test method to find the amount of combined water [11], specifies igniting the concrete at 1000°C and measuring the water driven off. This method cannot be used with blended cements. When these methods are used to find the w/c ratio, the results are likely to be within 0.1 [11], an accuracy of little practical value [1, p. 636]; the practical range of w/c ratio for concrete ranges from 0.40 to 0.70.

Therefore, a reliable test method for measuring the w/c ratio of concrete, especially during its early stage of curing (e.g. fresh concrete) would be very valuable to the construction industry. In addition, if a nondestructive testing method were developed that could reliably monitor the cure-state of concrete in the field, it would also have a tremendous practical influence in the construction industry, namely, early prediction of the strength of concrete members and quickened building of subsequent members on top of structures undergoing curing (i.e., support columns are examples of this).

II. Background

Microwave nondestructive techniques have shown great potential for evaluating dielectric materials [12], [13]. Microwave techniques are also capable of evaluating properties of materials composed of a mixture of several constituents. However, most of these studies have only considered physical mixing (i.e., no chemical interaction between constituents). Recent investigations have demonstrated the capability of microwaves to detect the state and degree of chemical reaction (curing) in several different materials in which curing takes place [14], [15]. As it is applied to cement-based materials, Zoughi *et al.*, used a simple microwave nondestructive method to detect the location of reinforcing steel in a concrete slab [16]. They showed the ability to manipulate the polarization properties of microwaves to enhance the image of a rebar. In that experiment they detected the presence of a separation in the steel bar as well. Their experiments also showed the sensitivity of microwaves to various aggregate size distributions. Subsequently, the potential of microwaves for detecting aggregate size distribution by manipulating the frequency of a microwave signal was demonstrated [17]. They also showed a strong correlation between the magnitude of the reflection coefficient of the microwave signal and hardened cement paste w/c ratio. Subsequently, through extensive measurements using open-ended rectangular waveguides, they showed a correlation between the magnitude of reflection coefficient and the compressive strength of cement paste (or w/c ratio) [18]. Later, they showed the potential of using monopole antennas for the same purpose [19]. Consequently, these promising results prompted a more extensive investigation in using near-field microwave nondestructive inspection techniques employing open-ended rectangular probes for evaluating constituent and cure properties of concrete.

As a result of these preliminary investigations, a more extensive study was embarked upon with the goal of near-field microwave characterization of cement-based materials using open-ended rectangular waveguide sensors. Thus far, these investigations have included inspecting mixtures of cement paste (water and Portland cement), mortar (water, sand, and Portland cement) and concrete (water, sand, aggregate, and Portland cement). The objectives of these studies have been such that learning about one mixture would lead into more understanding of the next. These investigations have shown that the magnitude of reflection coefficient increases as a function of decreasing w/c ratio for cured cement paste. At first glance this seems inconsistent with the fact that higher water content should render higher magnitude of reflection coefficient measured at a waveguide aperture. However, a closer look reveals that during the curing process water molecules bond with cement molecules, and the remaining free water evaporates. Thus, the water content becomes less and less free and more and more bound (to cement molecules) over time. The reason for this is that free water has much higher dielectric properties compared to those of cement powder, whereas bound water has similar to cement powder dielectric properties [20], [21].

The magnitude of reflection coefficient has been shown to be distinctly correlated to the w/c ratio of cement paste, and subsequently to its 28-day compressive strength (moist cured for three days in a hydration room and thereafter in air at room temperature) [18]. In mortar, a relationship between the standard deviation of the magnitude of reflection coefficient at higher frequencies and the s/c ratio of a mortar specimen, has been established [22]. Information on the w/c ratio of mortar specimens is obtained when the average value of the measurements is taken at lower frequencies. Mortar is a homogeneous dielectric mixture (even at 10 GHz), and a simple dielectric mixing model has been established that predicts the constituent volume content of mortar specimen [23]. Consequently, the porosity (volume content of distributed air) of a mortar specimen can also be determined. For concrete, it has been shown that lower microwave frequencies are suitable for determining w/c ratio, whereas higher frequencies may be used for determining the aggregate size and volume distribution [24]. It has been shown that at higher frequencies, the distribution of the measured magnitude of reflection coefficient is Gaussian, whereas at low frequencies the distribution is uniform. With the use of the modifiable parameters in each of these distributions, the constituent volume distribution of a given concrete mixture can be determined from its scattering characteristics [24], [25].

The results of the above studies, dealing with the near-field microwave nondestructive interrogation of cement-based materials, were concluded for cured specimens (i.e., specimen having cured for 28 days). In many practical applications the determination of the w/c ratio and the cure-state, would be beneficial in the early stages of curing. In this paper, the reflection properties of two Portland cement-based materials are investigated: cement paste and concrete. Measurements of the reflection coefficient are correlated to the w/c ratio and the cure-state. The presence of aggregates (fine and coarse) in cement-based materials has little impact on the curing process. Therefore, the properties of cement paste will be investigated for the understanding of this process. On the other hand, concrete is the most utilized Portland cement-based material in civil structures. Hence, studying the properties of concrete is needed to yield a more practical realm of application for this near-field microwave sensing technique.

Next, the procedure used for producing and curing of the test specimens, and the monitoring of their reflection properties is described. The near-field microwave reflection property measurement results are presented in relation to the w/c ratio and cure-state determination. A discussion describing the practical implementation of such a measurement system in the construction industry is also discussed.

III. Procedure

To conduct this investigation, several cubic cement paste and concrete specimens were produced each with a side dimension of 20.32 cm (8 in). In all cases, the specimens were moist cured in a hydration room for three days. Thereafter, the specimens were allowed to cure at ambient temperature and humidity for the remainder of the prescribed 28-day curing period. During this latter period, the reflection properties of the specimens were monitored daily using an HP8510B vector network analyzer in conjunction with an open-ended rectangular waveguide probe (see Fig. 1), at 5.0 GHz (G-band) and 10 GHz (X-band). The reflection coefficient, Γ, of the specimens referenced to the waveguide aperture were measured at several locations on all sides of the specimens omitting top and bottom. Subsequently, the average value of Γ was obtained. Twenty and 160 measurements were conducted at these frequencies. To ensure that the measurements were statistically independent, no overlapping areas were examined on any of the specimens (i.e., the spacing between each two measurements was greater than the probing waveguide aperture). For cement paste, this issue is not as critical since the mixture is very homogenous. As sand and aggregate are added to mixture to produce concrete, the point-to-point measurement variation becomes more important [22], [24].

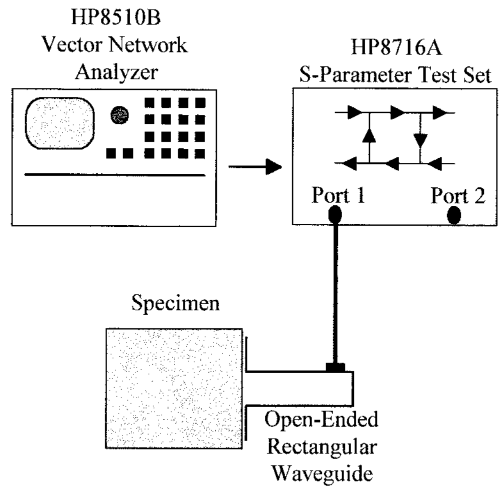

Fig. 1. Experimental setup.

IV. Experimental Results

A. Cement Paste

Cement paste is a homogeneous material resulting from the mixing of cement (Portland cement type II in the present study) and water. The proportion of water in the mixture is defined by the w/c ratio (measured by weight). Six cement paste specimens with w/c ratios of 0.35, 0.40, 0.45, 0.50, 0.55, and 0.60 were produced. Fig. 2 shows the results of the daily measurements of $|\Gamma|$ at 5 GHz (G-band). The measurements for cement paste were produced using a custom designed reflectometer, built from discrete microwave components. Although an adequate calibration procedure was conducted, the measurement precision cannot be compared to that of the HP8510B network analyzer. As discussed later, the cure-state prediction and early w/c ratio determination are based on the temporal behavior of $|\Gamma|$ (i.e., derivative of $|\Gamma|$ versus time). Also, any minute constant offset error term that is not corrected by the calibration will be nullified, when taking the derivative of the measurements of $|\Gamma|$ versus time. Therefore, the results obtained using the reflectometer are suitable for the analysis of the problem at hand.

The results in Fig. 2 indicate a rapid decrease in the measured $|\Gamma|$ during the first five days of curing, particularly for higher w/c ratio specimens. Physically, this is attributed to bleeding and subsequent evaporation of free water from

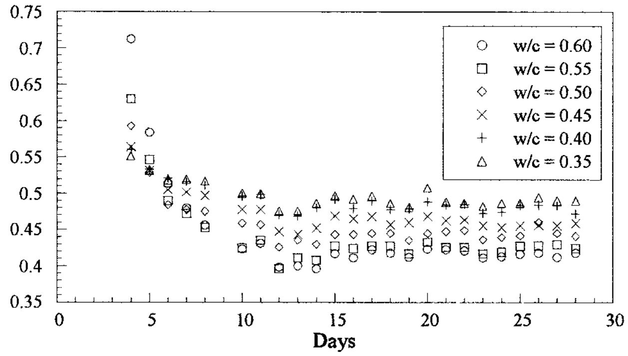

Fig. 2. Magnitude of reflection coefficient for cement paste specimens at 5 GHz.

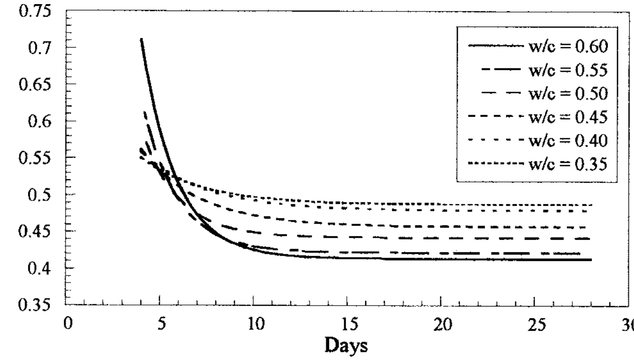

Fig. 3. Empirical representation of magnitude of reflection coefficient measurement over time for cement paste specimens at 5 GHz.

the surface of the cement paste blocks. Beyond the fifth day of curing, the measured $|\Gamma|$ for the 0.35 w/c ratio specimen remains consistently higher than those for higher w/c ratios. After the fifth day of curing, most of the free water is lost to evaporation if specimens cure at ambient humidity and temperature [26]. This indicates that any measurements of $|\Gamma|$ taken after the fifth day is indicative of the bound water in the specimen, more so than the free water. After the tenth day however, the measured $|\Gamma|$ is consistently higher for a lower w/c ratio.

Normally, the measured $|\Gamma|$ for a mixture consisting of a relatively low permittivity of dielectric constituent (cement) and a high permittivity dielectric constituent (water) is expected to increase as a function of increasing water content [27]. This is valid under the assumption that only physical mixing is present (i.e., before the hydration process begins). As seen in Fig. 2, this behavior is apparent in the first few days of curing. However, after the fifth day, the measured $|\Gamma|$ does not shown this trend. This indicates the presence of curing (i.e. a chemical reaction or hydration) in the specimens where the water is continually binding to the cement. Thus, the sensitivity of microwaves to the presence of water (free or bound) in cement paste, demonstrates the potential of using reflection property measurements as an indication of w/c ratio and curing in concrete structures [18]. Also, since the w/c ratio is directly proportional to the compressive strength of concrete [28], the electrical properties of these materials can be related to their mechanical properties, as has been shown for cement paste [18].

From Fig. 2 it is also evident that beyond the 14th day of the 28-day curing period, the temporal behavior of $|\Gamma|$, per w/c ratio, does not change very much and converges to its final value. Since sensing of the material using microwave energy interrogates the dielectric properties of the material on a molecular level, it can be assumed that the curing process is complete once the dielectric properties of these chemically active materials become constant. Therefore, by periodic monitoring of the reflection properties of the specimens during their curing process an estimate of the cure-state of the specimens, hence compressive strength can be ascertained. In all cases, the output power of the incident signal, into the cement paste infinite half-space, was set at 10 dBm. Upon doubling the output power (i.e., 13 dBm), and thus interrogating further into the specimen, no significant variation in the measurement of $|\Gamma|$ was observed. Also, since the temporal characteristic of $|\Gamma|$ is w/c ratio dependent, daily measurements of $|\Gamma|$ could be used to determine w/c ratio in the early stages of curing (i.e., fresh cement paste). Lastly, since the difference between the final values of $|\Gamma|$, for each w/c ratio, is experimentally measurable, these values can be used to monitor the w/c ratio of hardened cement paste, and subsequently can be related to its final compressive strength.

To better visualize the above assumptions, the temporal behavior of the measured $|\Gamma|$ for all w/c ratios was represented using a nonlinear curve fit, and the results are presented in Fig. 3. The curve fitting process was performed per w/c ratio, using the following expression:

$$|\Gamma|(t) = a + b\exp(-c \cdot t) \tag{1}$$

where a, b, and c are empirical coefficients and t represents time. These empirical coefficients are given in Table I as a function of w/c ratio for the results shown in Fig. 2. Also, included is the correlation factor R, which represents the quality of the fit ($R = 1$ representing a perfect fit). It is observed that the computed values of a, representing the final value of $|\Gamma|$ at the twenty-eighth day of curing, decrease as a function of increasing w/c ratio. This observation concurs with the conclusions made in [18].

Additional information can also be extracted from this table. The weighting coefficient of the exponential function, b, is smaller by an order of magnitude for the lower w/c ratio specimens compared to those with higher w/c ratio. At the time of mixing, the specimens with lower w/c ratios are represented by a much drier consistency than those with higher w/c ratio. In the construction industry, the consistency of a specimen is usually measured using a quantity defined as the slump [29, p. 80]. To measure this quantity, a cone (usually 12 in high) tapered from top to bottom is filled with the mixture. The cone is then removed and the mixture is allowed to slump down. The distance from which the mixture drops with respect to the height of the cone is defined as the slump. As crude as this measurement procedure might seem, the slump is usually required when using cement-based products in the construction industry as a means for quality control. Note that once the water content in cement paste exceeds a certain proportion (e.g., w/c of 0.45), the consistency of the mixture drastically

TABLE I
EMPIRICAL COEFFICIENTS OF (1) AS A FUNCTION OF w/c RATIO FOR CEMENT PASTE AT 5 GHz

	w/c ratio	a	b	c	R
Relatively dry	0.35	0.48782	0.21595	0.30709	0.916
	0.40	0.47964	0.26255	0.29935	0.945
	0.45	0.45756	0.37903	0.32166	0.958
Relatively fluid	0.50	0.44264	1.15070	0.51325	0.972
	0.55	0.42182	1.72460	0.52784	0.985
	0.60	0.41375	2.51960	0.53391	0.993

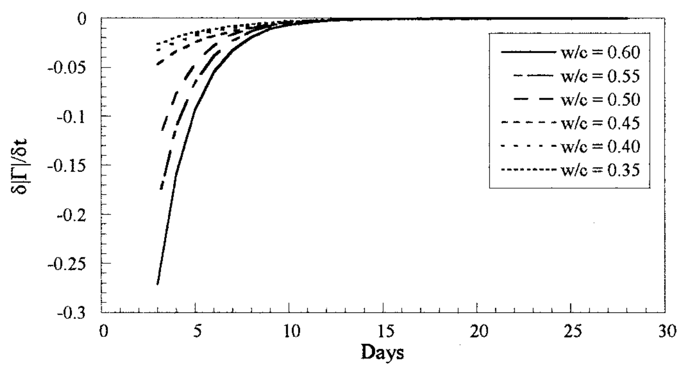

Fig. 4. Derivative of magnitude of reflection coefficient measurement over time for cement paste specimens at 5 GHz.

changes from a relatively consistent mixture to a fluid mixture. Therefore, the coefficient b can be potentially used as an indication of slump at the time of mixing.

The distinction between a dry and a fluid mixture is also apparent in coefficient c as a function of w/c ratio. Specimens with higher w/c ratio lose a significant portion of their water to evaporation in the first few days of curing. Thus, their respective exponential behavior, as shown in (1), are more pronounced. Therefore, the contribution of the weighting coefficient is expected to be more pronounced for these specimens, as shown in Table I. Since specimens composed of a relatively drier mixture lose much less water to evaporation, the relative change in their measured $|\Gamma|$ after the third day of curing is much less. It is interesting to observe that the coefficient remains relatively constant per the dry and per the fluid specimens. This observation may potentially be used as an indication of the workability (or slump) of the material. When the information provided by these three constants is combined, the result not only provides for the determination of the w/c ratio of cement paste at the time of mixing but also may provide an indication of the slump or workability of a mixture.

The w/c ratio of a mixture directly influences its compressive strength. Therefore, early w/c ratio prediction of cement paste is valuable in order to give an indication of the final compressive strength. The derivative of (1), with respect to time [$\delta|\Gamma|/\delta t$, as shown in (2)], is calculated for all the specimens and the results are presented in Fig. 4.

$$\delta|\Gamma|/\delta t = -b \cdot c \cdot \exp(-c \cdot t). \tag{2}$$

Two important features are apparent from this figure. First, for all w/c ratios, $\delta|\Gamma|/\delta t$ is zero after the 12th day of curing. Hence, it can be inferred that cement-based materials that have been moist-cured for three days and then left to cure at ambient temperature and humidity for the remainder of the prescribed 28-day curing period, are fully cured after 12 days. Recall that the specimens were deprived of any form of hydration after the third day of curing. Also note that no further curing will occur when the available free water has become fully bound to the cement or is lost to evaporation [29, p. 4].

The derivative of $|\Gamma|$, in the early days of curing, may be used to determine the w/c ratio in cement paste specimens. This is done by performing two or more measurements in the early days (or hours) of curing. The results for the rate of change in $|\Gamma|$ can be calculated and correlated to a w/c ratio as indicated in Fig. 4.

This early w/c ratio determination and cure-state monitoring of cement paste, using near-field measurements, is shown to be a practical and feasible evaluation tool. Although these findings constitute a potentially important improvement to the existing testing methods, the study will have more impact if it can be applied to the most commonly used cement-based material, namely concrete. Therefore, a similar study of concrete is presented next.

B. Concrete

Concrete is a heterogeneous material composed of cement, sand, coarse aggregate and water. The properties of concrete are dictated by three ratios: w/c, s/c, and ca/c ratio. The sand and coarse aggregate content is measured by volume with respect to the cement content. Although the measurement of the w/c ratio is the primary quantity under investigation in this paper, attention has already been devoted to determining the aggregate content in concrete [24]. This procedure utilized the statistical information of reflection property measurements of hardened concrete at S- and X-band for measurements conducted at the twenty-eighth day of curing. Near-field microwave reflection coefficient measurements, at lower frequency bands, were shown to correlate well for w/c ratio determination, whereas at higher frequency bands the aggregate size and volume distribution are primarily evaluated [24].

In this study, 16 concrete specimens were produced with w/c ratios of 0.50 and 0.60 and varying s/c and ca/c ratios of 1.0, 1.5, and 2.0, respectively. No specimens with s/c and ca/c ratio of 2.0 were produced, since their extremely dry consistency is impractical for construction purposes (i.e., lack of workability). The size of the aggregate used was

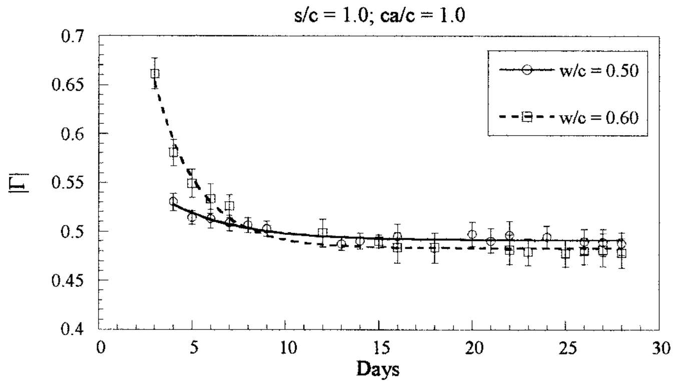

Fig. 5. Magnitude of reflection coefficient over time at 10 GHz for concrete specimens with w/c = 0.50 and 0.60, s/c = 1.0, ca/c = 1.0. (symbols) actual measurements, (line) empirical curve fit.

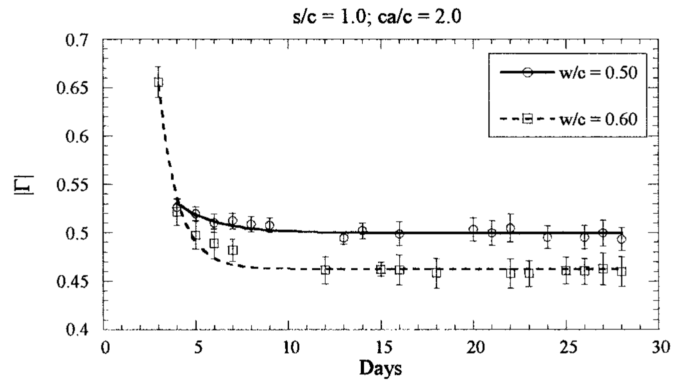

Fig. 7. Magnitude of reflection coefficient over time at 10 GHz for concrete specimens with w/c = 0.50 and 0.60, s/c = 1.0, ca/c = 2.0. (symbols) actual measurements, (line) empirical curve fit.

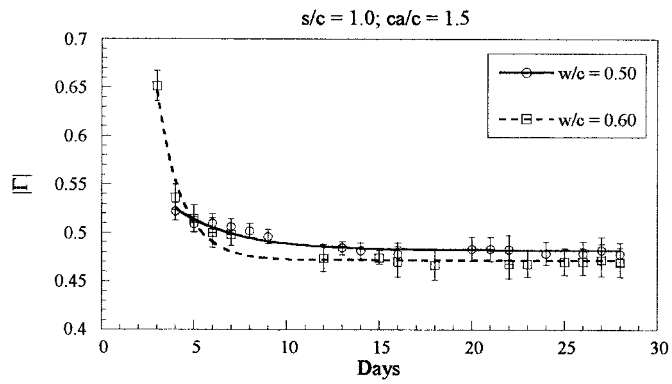

Fig. 6. Magnitude of reflection coefficient over time at 10 GHz for concrete specimens with w/c = 0.50 and 0.60, s/c = 1.0, ca/c = 1.5. (symbols) actual measurements, (line) empirical curve fit.

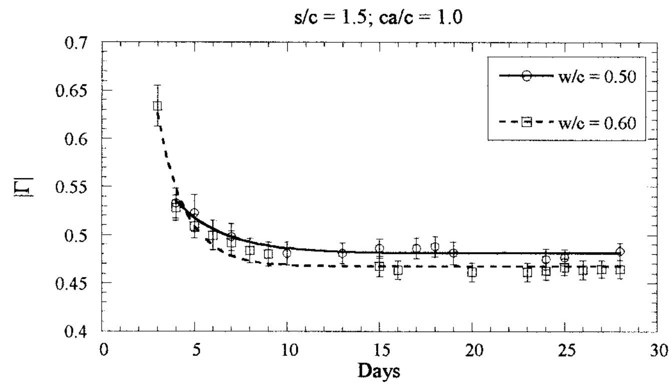

Fig. 8. Magnitude of reflection coefficient over time at 10 GHz for concrete specimens with w/c = 0.50 and 0.60, s/c = 1.5, ca/c = 1.0. (symbols) actual measurements, (line) empirical curve fit.

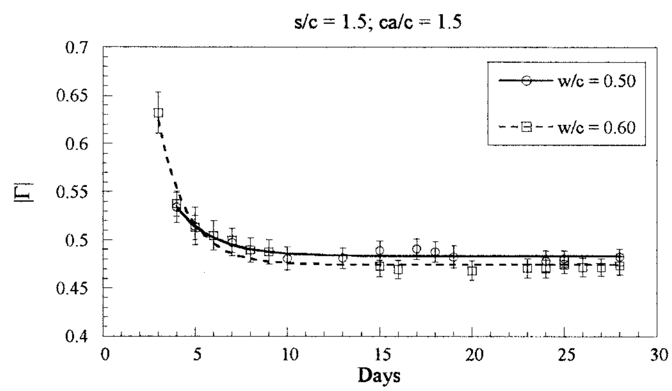

Fig. 9. Magnitude of reflection coefficient over time at 10 GHz for concrete specimens with w/c = 0.50 and 0.60, s/c = 1.5, ca/c = 1.5. (symbols) actual measurements, (line) empirical curve fit.

1.77 cm (0.5 in) for all specimens. Note that the presence of the coarse aggregate in the specimens causes point-to-point measurement variation due to scattering of the microwave signals by the aggregates. This scattering is expected to be more significant for higher microwave frequencies and respective smaller waveguide aperture dimensions, since the signal wavelength approaches the size of the aggregates. Therefore, at relatively high waveguide frequency bands, the point-to-point measurement variation can be used to determine the aggregate distribution [24]. The microwave reflection measurements for concrete were measured using the HP8510B network analyzer as shown in Fig. 1. In [24], only the microwave measurements of cured specimens were used to predict w/c ratio and aggregate distribution. This present study considers that the structure being tested in the field will be monitored for its reflection properties throughout its curing period. This provides additional information for evaluating the material content and cure-state of the specimen being tested, such as

- the variation of $|\Gamma|$ in the early stages of curing to provide for a w/c ratio prediction, as shown for cement paste;
- the final value of $|\Gamma|$ in the last stages of curing have also been shown to provide for a means for w/c ratio determination [24];
- the standard deviation of magnitude of reflection coefficient, $\sigma_{|\Gamma|}$, provides for an estimate of the aggregate content in a concrete specimen [24].

The aggregate content determination is shown to be best conducted at X-band [24]. As it will be shown here, the daily monitoring of $|\Gamma|$ at this waveguide frequency band also provides for the determination of w/c ratio. The ability to determine both of these parameters using only one waveguide frequency band (single frequency) simplifies the measurement procedure. Consequently, only X-band results will be discussed here. The experimental results (represented by discrete points) and empirical curve fits (represented by solid lines)

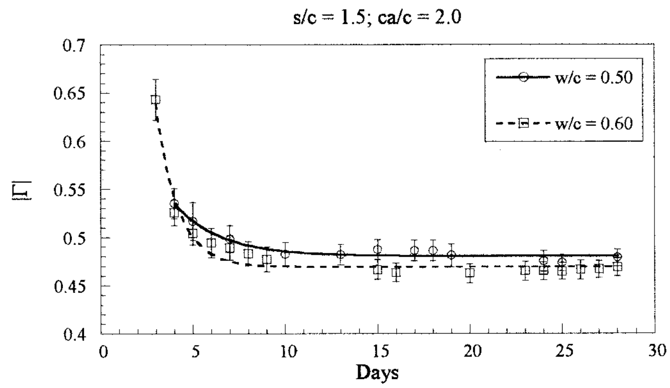

Fig. 10. Magnitude of reflection coefficient over time at 10 GHz for concrete specimens with w/c = 0.50 and 0.60, s/c = 1.5, ca/c = 2.0. (symbols) actual measurements, (line) empirical curve fit.

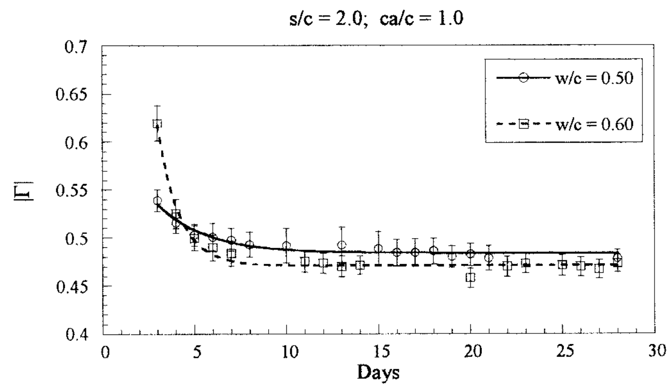

Fig. 11. Magnitude of reflection coefficient over time at 10 GHz for concrete specimens with w/c = 0.50 and 0.60, s/c = 2.0, ca/c = 1.0. (symbols) actual measurements, (line) empirical curve fit.

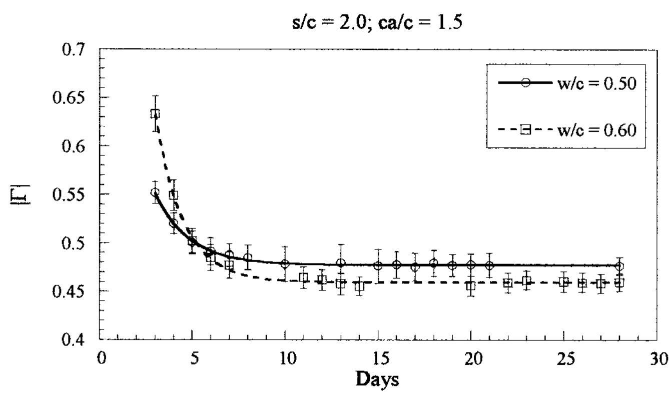

Fig. 12. Magnitude of reflection coefficient over time at 10 GHz for concrete specimens with w/c = 0.50 and 0.60, s/c = 2.0, ca/c = 1.5. (symbols) actual measurements, (line) empirical curve fit.

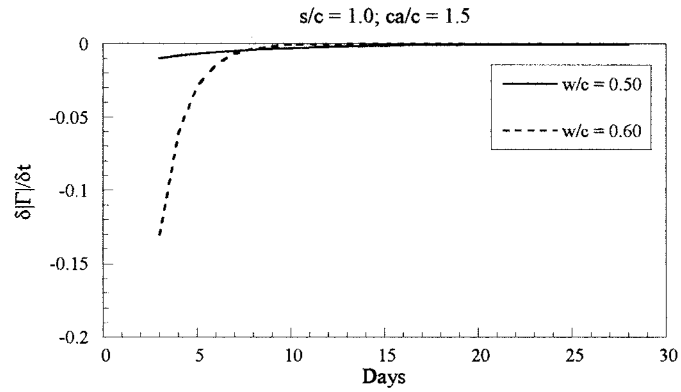

Fig. 13. Derivative of magnitude of reflection coefficient measurement over time at 10 GHz for concrete specimens with w/c = 0.50 and 0.60, s/c = 1.0, ca/c = 1.5.

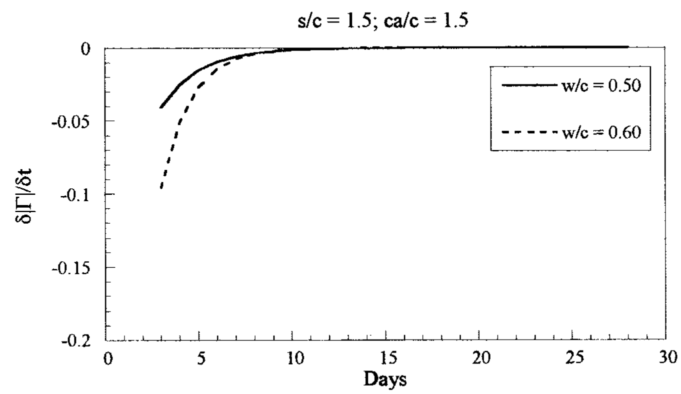

Fig. 14. Derivative of magnitude of reflection coefficient measurement over time at 10 GHz for concrete specimens with w/c = 0.50 and 0.60, s/c = 1.5, ca/c = 1.5.

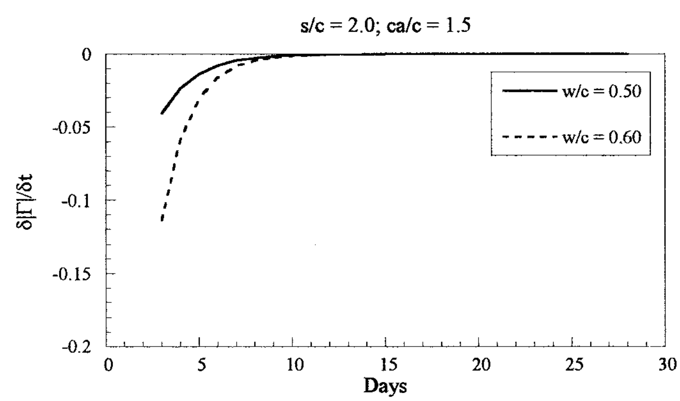

Fig. 15. Derivative of magnitude of reflection coefficient measurement over time at 10 GHz for concrete specimens with w/c = 0.50 and 0.60, s/c = 2.0, ca/c = 1.5.

of the reflection property measurements for all specimens are presented in Figs. 5–12. The results are paired by aggregate content with varying w/c ratio. For a given aggregate content, the specimens with lower w/c ratio will yield a higher compressive strength [29, p. 77]. In the construction industry, the control over the aggregate content is usually easier than that over the w/c ratio. It is for this reason that the results are given with varying s/c and ca/c ratios for each w/c ratio. This way the w/c ratio can be determined for a given aggregate content. In addition, the error bars contained in these figures represent one standard deviation of the magnitude of reflection coefficient, $\sigma_{|\Gamma|}$.

Two important observations can be made from these figures. In the latter stages of curing and for all cases, the specimens with w/c of 0.50 consistently had a higher reflection coefficient than those with w/c ratio of 0.60. This corroborates the previous findings presented in [18] and [24]. Furthermore,

TABLE II
EMPIRICAL COEFFICIENTS OF (2) AS A FUNCTION OF w/c RATIO AND s/c RATIO FOR CONCRETE WITH A ca/c RATIO OF 1.5 AT 10 GHz

s/c ratio	w/c ratio	$-b \cdot c$	c
1.0	0.50	0.017919	0.1895
	0.60	1.22844	0.74823
1.5	0.50	0.17463	0.48961
	0.60	0.63751	0.63364
2.0	0.50	0.21065	0.45837
	0.60	0.80839	0.65515

as in the case of cement paste, the variation in the temporal measured $|\Gamma|$ is much more pronounced in the early days of curing for the 0.60 w/c ratio specimens than that for the 0.50 w/c ratio specimens. Although the difference in measured $|\Gamma|$ versus w/c ratio in the first days of curing is important, the overall dynamic range of this parameter (as a function of days) is much less than that for cement paste. This is explained by the fact that the cement paste phase occupies a much smaller portion of the overall volume in concrete. Therefore, the reflection properties of concrete are weighted by its volume fraction of cement paste in the specimen. Nevertheless, the difference between the rate of change between the two w/c ratios per given s/c and ca/c ratio is still significant.

For brevity, the derivative of $|\Gamma|$ for the concrete specimens with 1.5 ca/c ratio and varying s/c ratio are presented in Figs. 13–15. Again, it can be noticed that the derivative of $|\Gamma|$ is null after the twelfth day of curing. This corresponds to the day at which the reflection property measurements of cement paste converged to their final value. Since the cement paste phase of concrete is typically the only chemically active component (e.g., no aggregate chemical reaction), there should not exist any significant change between the curing rate of concrete and cement paste. This assumption takes into consideration that both materials have been cured in relatively the same temperature and humidity conditions. The results of Figs. 4 and 13–15 clearly indicate this. Hence, microwave near-field sensing of Portland cement-based materials for their cure-state monitoring, is feasible and more importantly, can be conducted in a practical fashion. Since the cure-state should primarily be determined by the gradient of $|\Gamma|$ with respect to time, Table II presents the empirical constants of (2) for the six concrete specimens. As expected the weighting coefficient, $-b \cdot c$, is more pronounced for the specimens with higher w/c ratio regardless of the aggregate content, compare to the specimen with 0.50 w/c ratio. The same holds true for the coefficient influencing the decaying exponential behavior of the derivative of $|\Gamma|$ with respect to time.

V. DISCUSSION

As indicated by the measurement results, the reflection properties of Portland cement-based materials are mainly dictated by the w/c ratio. Other constituents such as the sand and coarse aggregate content also influence the measurement of $|\Gamma|$, however to a much lesser extent, since these constituents typically do not contribute to the curing process. This fact was demonstrated as the measured $|\Gamma|$ for cement paste and concrete were both shown to converge to their final value after the twelfth day of curing. This corroborates the findings by Maekawa *et al.* performed using nonmicrowave techniques [30]. In this reference cement-based materials, which were moist cured for two days and then air cured for the remainder of the curing period, did not present any curing behavior past the twelfth day of curing. The results of our microwave investigation clearly indicate that the w/c ratio can either be monitored using the gradient of change in temporal measurements of $|\Gamma|$ during the first days of curing, or using measurements taken in the final stages of curing. However, using the temporal variation of the measurements does present practical advantages. Since the dynamic range of the measured values for the gradient, per w/c ratio, is much more pronounced than the difference in $|\Gamma|$ for the final days of curing, this provides for higher sensitivity when determining the w/c ratio. Once a collection of data is acquired, a simple numerical routine can be implemented to determine to which empirical curve, the data most closely corresponds to. Also, if more measurement points are taken in the early stages of curing, the contribution of any erroneous measurement resulting from operator error or such, will be minimized.

Cure-state monitoring is actually a less ambiguous process of the two. As described previously, since microwave sensing interrogates the dielectric properties of the material under test, the curing process is assumed complete when there is no significant variation in the daily measurements of $|\Gamma|$ [21]. Also, since the cement paste jell phase in concrete is the only portion undergoing curing, the experimental curing periods of cement paste and concrete were shown to be similar, as expected. The simple concept behind this measurement procedure is very attractive since it requires very little data interpretation. This is even more important since the eventual targeted operators of such a technology will, at best, be novice in the field of microwave engineering. Lastly, since the measurement procedure only requires the measurement of $|\Gamma|$, a very simple setup is required (e.g., a calibrated reflectometer used for cement paste specimens). Although near-field in-contact measurements can be sensitive to pronounced surface variations, measurements with slight standoff can be successfully used to monitor the reflection properties of the material as demonstrated in [31].

VI. CONCLUSIONS

In this paper, a preliminary study investigating the reflection properties of Portland cement-based materials for w/c ratio and cure-state determination was performed. The proposed technique provides for a significantly better alternative than the existing destructive techniques. Although the results are promising, further investigations must be performed to fully validate this technique. The effect of humidity and temperature of environment in which the specimen is left to cure, and the depth at which the microwave energy senses the material, must also be investigated. This last item would serve to put an upper bound on the size of the structures that could be monitored. Also, other limitations of this technique must be ascertained. Among them, the impossibility of monitoring the curing properties of moist-cured concrete, due to the constant presence of the free water on the surface of the material. Notwithstanding these possible limitations, the proposed technique possesses an inherent potential to surpass the utility of all current testing techniques.

Last, microwave near-field sensing techniques, such as this one, are also useful for quality control purposes of a mixture in its early stages of curing. A direct application of this method would be to determine the water loss in the mixture due to the somewhat porous nature of the sand and aggregate. The moisture content of the sand and the aggregate added to a mixture are not uniform and difficult to control in practice. If not properly hydrated, these aggregates will absorb a portion of the mixing water, changing the w/c ratio of the mixture and hence its compressive strength.

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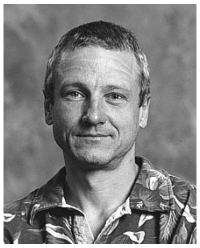

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